Single Sideband Optical Signal Generation and Chromatic Dispersion Compensation Using Digital Filters

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Abstract *We show, for the first time, that signal processing for single sideband signal generation and dispersion compensation can be implemented using digital filters. Clear eye opening at 40km of standard fibre at 40Gb/s is demonstrated.*

Introduction

Electronic signal processing techniques are attractive for the compensation of impairments such as chromatic dispersion (CD) in optical fibre communications links as they avoid the use of expensive and bulky optical components. Proposed techniques include decision feedback equalisation [1,2] and maximum likelihood sequence estimation [3]. However, as phase information is not transfered into the electrical domain after square law detection of double sideband format signals the increase in range that can be obtained using these techniques is limited to a factor of two [4].

An alternative solution which has the potential for greater range is the transmission of single sideband (SSB) optical signals, which results in the optical phase being transfered into the electrical domain and hence allows linear electronic filters to be used for compensation [5]. Previous work has demonstrated compensation of 10Gb/s signals using microstrip [5,6] or SiGe analog filters [7]. However, the use of digital techniques in the transmitter as well as in the receiver compensator could enable the technique to be implemented with low cost integrated circuits, for example using silicon CMOS technology [8]. This paper describes 40Gb/s simulations showing, for the first time, that the signal processing both for SSB drive signal generation in the transmitter and the CD compensation in the receiver can be implemented using low complexity digital filters.

SSB Transmitter

The simulated optical SSB transmitter (figure 1) used a dual electrode Mach-Zehnder (MZ) modulator driven by signals obtained from a 40Gb/s 1024-bit pseudo-random binary sequence (PRBS) generator. To generate the two MZ drive signals, the Hilbert transform of the PRBS digital signal must be obtained. For this purpose, a four tap digital finite impulse response (FIR) filter was used, with an output given by [5]:

$$\hat{x}(n) = \frac{2}{3\pi}x(n) + \frac{2}{\pi}x(n-2) - \frac{2}{\pi}x(n-4) - \frac{2}{3\pi}x(n-6) \qquad (1)$$

where *x(n)* is the PRBS sampled at twice the communication bit rate. The outputs of the 6-bit digital to analog converters (DAC) were amplified with appropriate bias to produce two drive signals [5]:

$$d_1 = mV_\pi\left[x + \hat{x}\right] - \frac{V_\pi}{4} \qquad d_2 = mV_\pi\left[-x + \hat{x}\right] + \frac{V_\pi}{4} \qquad (2)$$

where V_π is the modulator switching voltage and m controls the extinction ratio. These signals were filtered by low pass 6th order Bessel filters, having a 3dB bandwidth of 30GHz, and applied to the Mach-Zehnder modulator inputs. The electric field of the transmitted SSB signal is then given by [5]:

$$E_{out} = \frac{E_{in}}{2}\exp\left(\frac{j\pi d_1}{V_\pi}\right) + \frac{E_{in}}{2}\exp\left(\frac{j\pi d_2}{V_\pi}\right) \qquad (3)$$

where E_{in} is the output of the CW laser. An optical signal with an extinction ratio of 6dB was used in all simulations. The low number of Hilbert filter taps and the limited DAC resolution did not significantly impair the overall system performance.

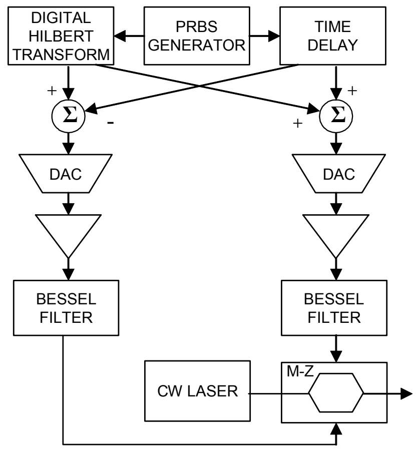

***Figure 1**: SSB transmitter block diagram*

The effect of fibre dispersion was modeled using the transfer function:

$$H(f) = \exp\left(\frac{j\pi DL\lambda^2 f^2}{c}\right) \qquad (4)$$

where D is the fibre dispersion, L is the fibre length, λ is the laser wavelength and *f* is the frequency offset from the carrier. The effects of fibre non-linearity and noise were not considered in the simulation.

Compensating Receiver

The simulated receiver is shown in figure 2. After square law detection, the electrical signal was sampled over the full signal magnitude with 6 bit resolution.

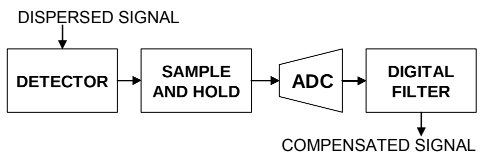

***Figure 2**: Receiver block diagram*

The sampling and subsequent digital processing were investigated at both the bit rate and twice the bit rate (i.e. 40GSa/s and 80GSa/s for 40Gb/s communication). The sampling timing was synchronised to the bit-rate and optimised to achieve the best eye opening. The compensating filter was an infinite impulse response (IIR) all-pass digital filter having a group delay response designed to compensate for the effects of CD only. A commercially available filter design package which allows the use of arbitary group delay constraints was used. Using 40GSa/s processing, it was only possible to design the desired reponse from DC to 20GHz, whereas 80GSa/s allowed DC to 40GHz design. However, a lower order filter was required to produce a good approximation to the desired response at 40GSa/s. In the results presented here, a 5th order filter was used for 40GSa/s simulation and 15th order for 80GSa/s. Increasing the filter order above these values to obtain a more accurate fit to the desired response or increasing the ADC resolution produced only a very limited improvement in overall system performance. Figure 3 shows examples of the group delay response of filters designed for several ranges of standard fibre (D = 17ps/nm.km) demonstrating good linearity (±5% ripple).

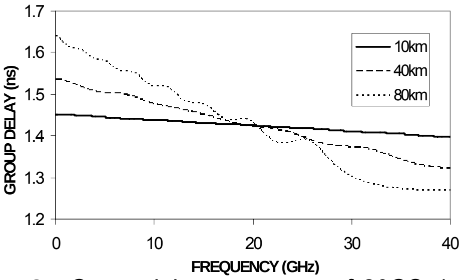

Figure 3 *: Group delay responses of 80GSa/s filters for compensation of various standard fibre lengths*

Transmission Results

Figure 4 shows the transmitted SSB spectrum. A vestige of the upper unwanted sideband is retained due to the non-linear characteristic of the modulator.

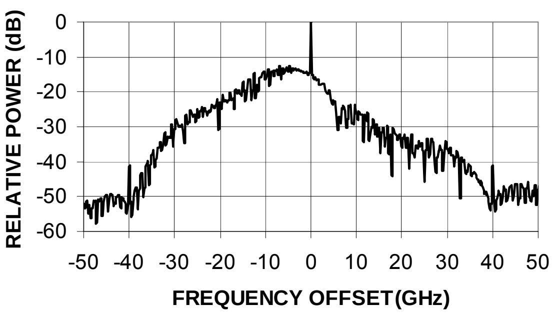

Figure 4*: 40Gb/s SSB spectrum*

However, a good quality eye is produced (figure 5a). Figure 5 also shows digital eye diagrams for a 40km link of standard fibre compensated using 40GSa/s (figure 5c) and 80GSa/s processing (figure 5d) compared with the uncompensated analog eye (figure 5b). The unusual shape of the compensated eyes is due to the limited number of sample points per bit period. Figure 6 shows the eye opening versus dispersion and equivalent length of standard fibre obtained at both sampling rates. In the noise free simulation, a range of 60km was achieved before complete eye closure with 40GSa/s processing, while over 100km was achieved with 80GSa/s. The practical achievable range will depend on the noise performance of the link. For comparison, the uncompensated dispersion limited range for a normalised eye opening of 0.5 (3dB) is approximately 5.5km at 40Gb/s.

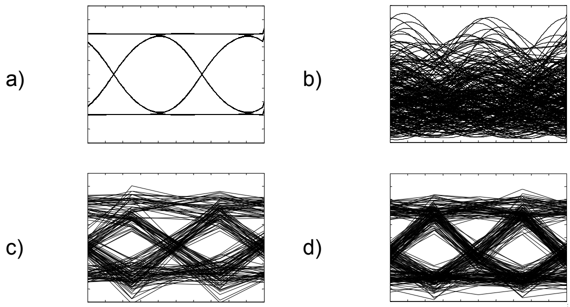

Figure 5*: Eye diagrams for a 40km link (a) transmitted analog SSB eye (b) uncompensated analog eye at receiver (c) compensated digital eye with 40GSa/s and (d) 80GSa/s sampling. (5ps/div)*

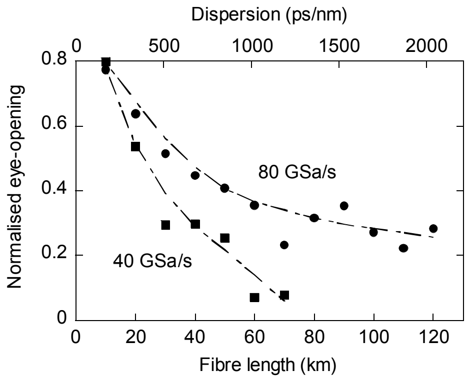

Figure 6*: Eye opening versus dispersion and range for 40GSa/s and 80GSa/s processing*

Conclusions

We have shown for the first time that simple digital filters can be used for SSB optical signal generation and electronic chromatic dispersion compensation. We demonstrated dispersion tolerance of up to 2000ps/nm dispersion (equivalent to over 100km of standard fibre) at 40Gb/s with sampling at twice the bit rate. Good system performance is possible with low DAC and ADC resolutions (6-bit) and low order digital filters. These results demonstrate the feasibility of highly effective integrated circuit based adaptive compensation schemes.

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